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APPLICATIONS OF INTEGRATED DESIGN/ANALYSIS SYSTEMS  
IN AEROSPACE STRUCTURAL DESIGN

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## INTRODUCTION

Many papers have been written on structural optimization techniques and integrated design and analysis systems; however, engineering managers, project engineers and design engineers still ask the questions: Are structural optimization techniques of academic interest only, or are they really being used on actual hardware designs in a real production environment? And, if these techniques are being used, do they really contribute to the structural design? Also, are optimization tools being used as an integral part of the overall design/analysis systems that various companies are either currently using or plan on developing? Our paper will attempt to answer these questions by reviewing development efforts and the application of the resulting systems to actual hardware designs that have been developed and manufactured at Grumman Corporation.

Many papers have been written on structural optimization techniques and integrated analysis and design systems. Yet, many design engineers ask

- Are structural optimization techniques of academic interest only, or are they really being used in a production environment? If so, do they really contribute to the design of a structure?
- Are optimization techniques being used as an integral part of the overall design/analysis systems that various companies are currently using and/or developing?

## DEVELOPMENT OF AUTOMATED STRUCTURAL DESIGN/ANALYSIS SYSTEMS AT GRUMMAN

Structural engineers at Grumman have been active in developing and applying structural analysis and optimization tools for many years. Grumman was among the pioneers in the development of the force method in the late 1940's (Ref. 1) and continued using that technique on many company projects until the early 1960's. In 1963, we began developing ASTRAL (our Automated Structural Analysis System) which is based on the direct stiffness (displacement) method. The analysis and design of the Lunar Module really forced this to occur, inasmuch as the force method could not cope efficiently nor adequately with the complex structural configuration of that vehicle.

Use of the direct stiffness method led us, in 1964, to develop a program that permitted us to cycle the analysis in conjunction with automated element resizing procedures. Today, we call this approach "Fully Stressed Design" (FSD). Our early FSD program (Refs. 2 and 3) was used in the design of the EA-6B wing and ultimately led to the development of the ASOP program (Automated Structural Optimization Program). Initially, ASOP was developed to handle metallic construction; later, in 1969, it was extended to composites.

- 1948 - Development of force method - Wehle & Lansing
- 1963 - Development of displacement method - ASTRAL system
- 1964 - Development of fully stressed design (FSD) capability
  - ASOP program for metallic structures
- 1967 - Development of IDEAS - integrated analysis procedures in 8 disciplines (Integrated DEsign and Analysis System)
  - applied to design of F-14

DEVELOPMENT OF AUTOMATED  
STRUCTURAL design/analysis SYSTEMS  
AT GRUMMAN (CONTINUED)

Obviously, one cannot analyze a structure without applied loads and, likewise, cannot predict flight and ground loads without knowledge of the elasticity of the vehicle. In 1967, when facing a potential, major new design contract (that was to become the F-14), we embarked on the development of a comprehensive computer system that would address the overall external and internal loads problem. We called the system IDEAS (Integrated Design and Analysis System, Ref. 4) and used it extensively in the design of the F-14 fighter and in preliminary designs of the Space Shuttle (Refs. 5 - 7). IDEAS was a batch-oriented system in which special care was given to consistent I/O between the various modules that comprised the system. Later, the concepts behind the IDEAS system were extended to a time share environment and the development of the RAVES system (Rapid Aerospace Vehicle Evaluation System - Ref. 8).

- 1969 - Extension of ASOP to composite construction
- 1972 - Development of RAVES (Rapid Aerospace Vehicle Evaluation System) time share system - considered 15 disciplines
- 1973-1981- Development of FASTOP system
  - flutter constraints, aeroelastic effectiveness, divergence speed
- 1975 - Development of GEMS system -- interactive graphics
  - IBM 2250 --3250 -- 5080 -- GIP system
  - uses CADAM, CATIA on IBM main frames via 5080 scopes

DEVELOPMENT OF AUTOMATED  
STRUCTURAL DESIGN/ANALYSIS SYSTEMS  
AT GRUMMAN (CONTINUED)

Between 1973 and 1981, Grumman was active in developing optimization procedures for combined strength and aeroelastic requirements (Refs. 9 - 22). A major computer program that was developed in this time frame was FASTOP (Flutter and Strength Optimization Program). This program, which received Air Force sponsorship, was one of the first major systems to incorporate strength and aeroelastic constraints in one design/analysis system.

In 1975, the company began developing our CAD/CAM "GEMS" system (Grumman Engineering and Manufacturing System). This system embodies various commercial programs such as CADAM, CATIA and PATRAN and operates on IBM mainframes via 5080-type scopes. Our in-house developed design/analysis system, COGS, operates in this same interactive graphics environment, making use of the same equipment used by our designers and manufacturing engineers.

COGS derives its flexibility from the ASTRAL-COMAP system that has been used at Grumman for many years on virtually all major projects that require structural analysis. This system is constantly upgraded to reflect new changes in hardware, software and the interactive graphics environment.

COGS places strong emphasis on interactive graphics and has an extensive analysis capability. For example, using COGS, an engineer can generate a structural finite-element model, a lifting surface airloads model, or a dynamic transient response model. He can calculate aerodynamic influence coefficients, aerodynamic node loads, and inertia loads due to flight or ground loading conditions. He can transform these loads from their respective models to the structural model and can calculate and interactively plot moment, shear and torsion curves, as well as envelopes of these curves, on a 5080 scope. He can also calculate internal loads, stresses and strains, nodal deflections, vibration modes and frequencies, flexibility coefficients, and buckling loads and mode shapes. The system can also perform multilevel substructuring, thermal analysis, plastic analysis, nonlinear variable contact analysis and crack growth analysis. A given model, once analyzed, may be resized for strength or for other constraints such as those dictated by aeroelastic or frequency requirements. (Here, we have incorporated portions of the FASTOP code into COGS.) The user may also perform a wide variety of user-specified matrix operations.

Graphical output may be viewed at the scope or plotted via a batch submittal to a Versatec plotter for hard copy. Buffer plots of any scope display may be obtained by requesting a "buffer dump" at the scope and then plotting these data on the Versatec. In addition, hard copy of color graphics that show contours of stresses, composite ply layups, derivatives of frequency with respect to element gage, plus a wide variety of other information,

DEVELOPMENT OF AUTOMATED  
STRUCTURAL ANALYSIS/DESIGN SYSTEMS  
AT GRUMMAN (CONCLUDED)

may be obtained from a Seiko D-SCAN plotter that is attached to selected scopes. We usually plot full E-size or J-size drawings showing such data as internal panel loads, average stresses or strains, ply layups, cap loads and shear flows, element gages, nodal deflections or mode shapes.

As a subsystem of GEMS, COGS runs interactively on the IBM 3090, or compatible mainframes like the NAS 9060. We have attached an FPS-164 to one of the 3090 mainframes in order to provide a 10 Mflops capability for real-time, computer-intensive calculations while, at the same time, off-loading the mainframe so that these calculations do not interfere with other interactive systems. COGS presently interfaces with CADAM and will interface with CATIA in the future. Grumman has worked with PDA Engineering and acted as a beta test site for developing a 5080 fully interactive graphics version of PATRAN. Thus, our COGS structural analysis system is very much entwined with the same computing hardware, software and system that is used to perform computer-aided design and computer-aided manufacturing.

We have used COGS on a wide variety of company projects including: Gulfstream-III, PDX TOKAMAK, M-161 Hydrofoil, F-14, C-2A, E-2C, Dehavilland DASH-8, A-6F, V-22, EA-6B, X-29, Orbiting Maneuvering Vehicle, Space Based Radar, CW/VT (Composite Wing and Vertical Tail Program), and C-17 Control Surfaces.

- 1976 - Development of strength resize capability in ASTRAL
- 1978 - Development of COGS system (subsystem of GEMS)
  - ↓ Applications: G-III, PDX TOKAMAK, M161 Hydrofoil, F-14, C-2A Reprocurement, E-2C, Dehavilland DASH 8, A-6F, V-22, EA-6B, X-29, OMV, SBR, NPBIE, CW/VT, C-17 control surfaces
- 1983 - Development of COGS system as major interactive graphic structural analysis capability - incorporate FASTOP optimization capability, add flight loads, ground loads, weights, and thermal analysis capability
  - ↓
- 1987 - Conversion of system to PHIGS standard -- increase interactive graphics capability

## OBJECTIVE OF THE COGS SYSTEM

The objective of the COGS system is to provide a capability for analyzing and designing structures in a fully integrated interactive graphics environment. The word "analyzing" implies the ability to calculate all external loads due to various conditions such as maneuvers, gusts, landing, catapulting, taxiing, thermal environment as well as calculating the response of the structure to these loads. The word "designing" implies sizing the structure so as to maintain structural integrity and satisfy specified performance requirements throughout the complete flight envelope.

We do not mean to imply that we have linked our finite-element structural analysis and optimization capability directly to CADAM-type shop drawings; however, if we are ever going to achieve this type of objective in the future, the system upon which to build is in place in an interactive graphics environment.

The objective of the COGS system is to provide a capability for

### ANALYZING and DESIGNING structures

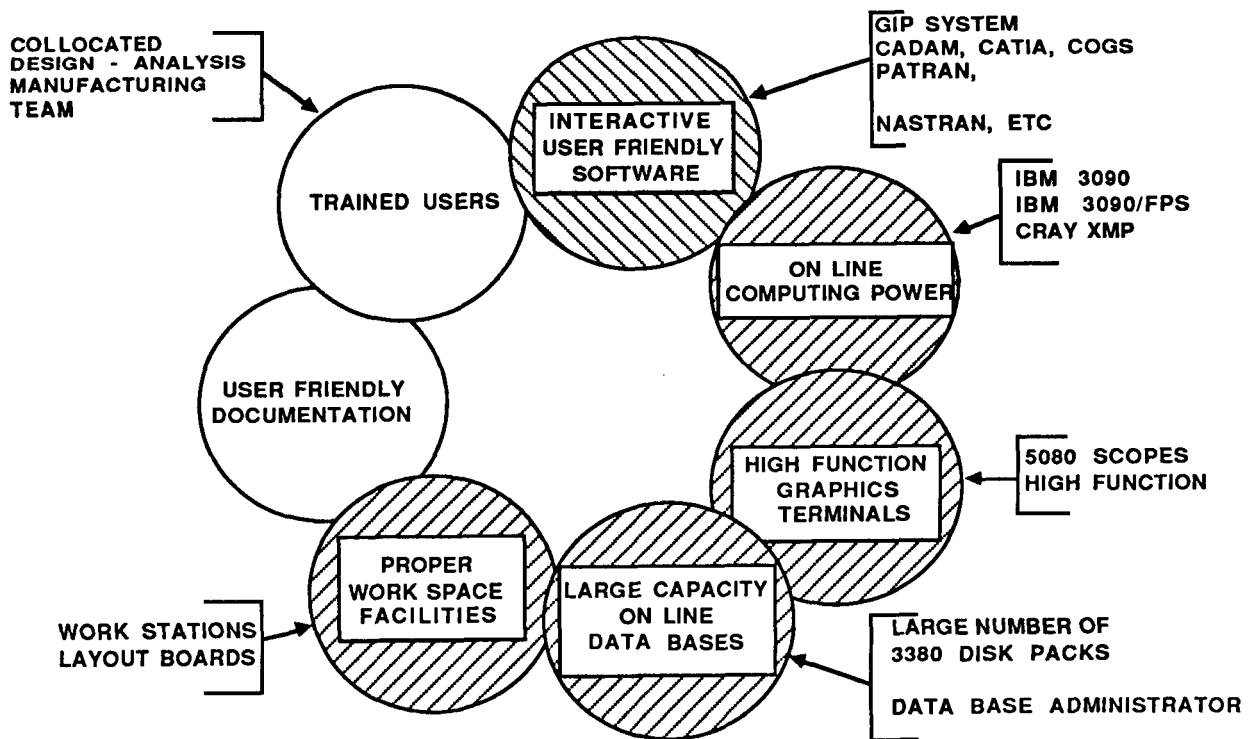
ANALYZING implies the ability to calculate all external loads due to various conditions such as flight maneuvers, gusts, landing, catapulting, taxiing, thermal environment as well calculating the response of the structure, such as internal loads.

DESIGNING implies sizing the structure so as to maintain structural integrity and specified performance throughout the complete flight spectrum.

# THE INTERACTIVE GRAPHICS ENVIRONMENT

Many elements make up the environment for the performance of structural analysis, optimization and design. We certainly need software, and at Grumman our GEMS system embraces and supports CADAM, CATIA, PATRAN, NASTRAN and, of course, our in-house COGS system. GEMS operates on 5080 high-function scopes and utilizes IBM 3090 mainframes. We also have access to a Cray and have an FPS-164 attached to the 3090 to provide on-line computing support and to off-load the mainframe. We have a large number of disk packs for storing data and have design facilities in all of our design and manufacturing plants for properly using the system.

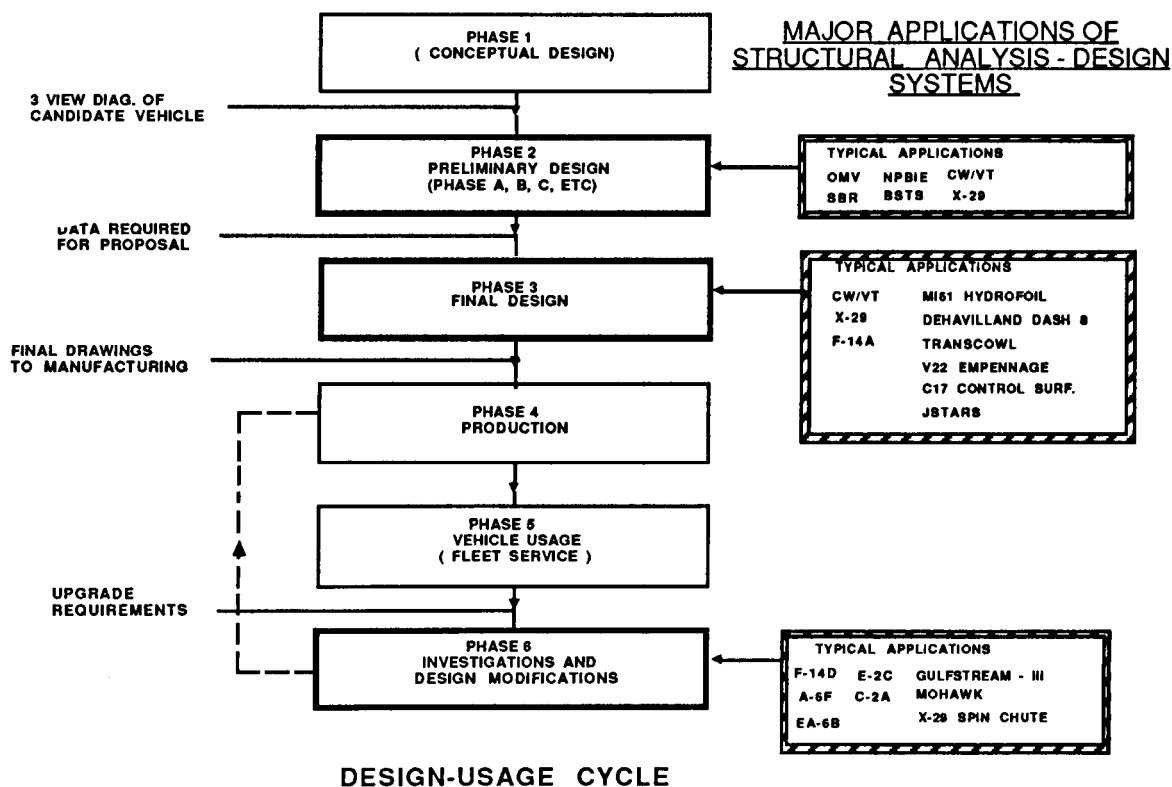
Our trained users are rapidly becoming part of collocated design/analysis/manufacturing teams.





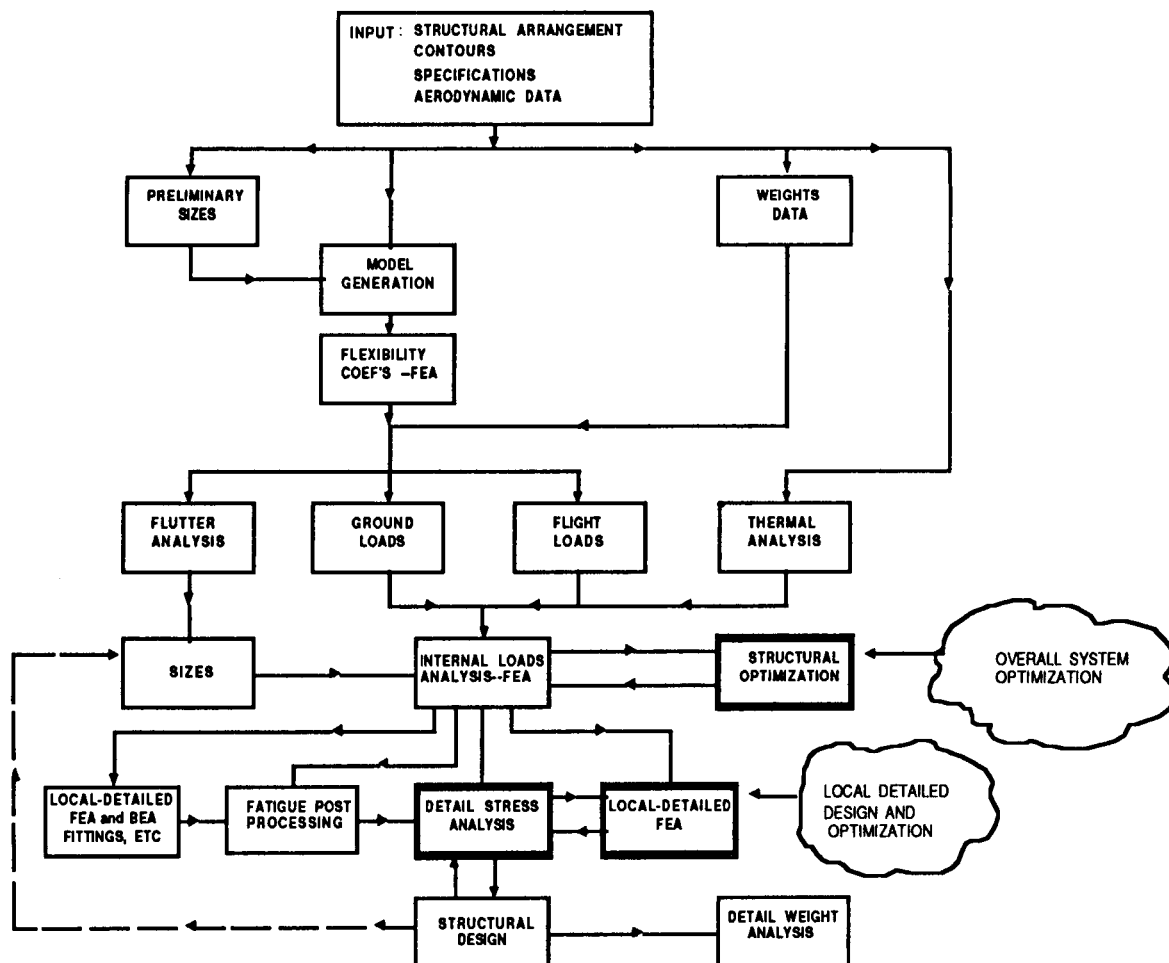
## DESIGN-USAGE CYCLE

The design-evolution cycle for a given vehicle may be divided into six phases. Phase 1, Conceptual Design, is basically parametric in nature. Finite-element analysis and optimization techniques are usually not applied in this phase. Phase 2, Preliminary Design, begins with a 3-view drawing of the candidate vehicle and progresses until enough information is gained to prepare a proposal for hardware design. Our structural optimization procedures and the COGS system have been used extensively in this phase of design on a wide variety of vehicles. Phase 3, Final Design, begins after award of a hardware proposal and progresses until all drawings have been released to manufacturing. Clearly, structural analysis and optimization techniques play an important role. In Phases 4, Production, and 5, Vehicle Usage, systems such as COGS are used primarily for investigations related to local problem solving. Phase 6, Investigations and Design Modifications, is concerned with design upgrading for improved vehicle performance or extended life.



## TYPICAL DESIGN/ANALYSIS CYCLE

The major tasks that are undertaken in a typical analysis/design cycle are shown in the figure below. This basic flow diagram pertains to the tasks that are performed in Phases 2, 3 and 6, the differences being in the degree of refinement of the analytical models. The arrows indicate the primary direction of the flow of calculation. In actual application, much churning and internal looping is performed which is not shown. This says much about how one must construct rather general analysis modules and supportive data bases which permit entry and exit from almost any task in the cycle. Our intent here is not to discuss the total analysis cycle and its many subtasks, but rather to concentrate on the structural optimization tasks that are shown in boldface.



APPLICATIONS OF OPTIMIZATION PROCEDURES TO  
ACTUAL DESIGN AT GRUMMAN

PHASE 2 -- PRELIMINARY DESIGN

We used the FASTOP system extensively in the preliminary design phases of the X-29 (Ref. 23) and we will elaborate on this later.

We also used our ASTRAL/COGS system to perform element resizing for frequency avoidance on several space type structures. Two examples are the preliminary sizing for the OMV and NPBIE.

**PHASE 2 -- PRELIMINARY DESIGN**

- X-29 - use of FASTOP to optimize structure for divergence avoidance -- evaluate laminate configurations
- OMV - Orbiting Maneuvering Vehicle  
use of ASTRAL/COGS -- multiple frequency avoidance
- NPBIE - Neutral Particle Beam Ionization Experiment  
use of ASTRAL/COGS -- frequency avoidance

## APPLICATIONS OF OPTIMIZATION PROCEDURES TO ACTUAL DESIGN AT GRUMMAN

### PHASE 3 -- PRODUCTION

We have employed structural optimization techniques in the production phase on a number of vehicles. In the 1960's, the ASOP program was used to size the EA-6B wing cover (Ref. 2). Later, an upgraded version of this program allowed Grumman to size the F-14 boron-epoxy composite horizontal stabilizer.

The Gulfstream III wing was sized using the fully stressed design capability within ASTRAL-COMAP. Here, a COMAP verb, RESIZE, performs the sizing by calling a subprogram that sizes integrally stiffened construction (Ref. 20).

The X-29 graphite-epoxy, composite, forward-swept wing was sized in the PD phase for divergence avoidance. Gages were maintained as minimums in the final design phase in which the wing was resized for strength using the ASTRAL/COMAP RESIZE capability.

The CW/VT (Composite Wing and Vertical Tail) were sized to meet strength and control-surface effectiveness requirements by making use of the optimization modules contained in our COGS system. We will discuss this in more detail later.

### PHASE 3 -- PRODUCTION

- EA-6B wing - use of FSD (early use of ASOP program).
- F-14 boron-epoxy composite horizontal stabilizer - ASOP program.
- Gulfstream-III wing - use of ASTRAL resize capability
  - integrally stiffened panel.
- X-29 graphite-epoxy composite forward-swept wing
  - use of FASTOP in P.D. phase - divergence avoidance
  - use of ASTRAL resize in final design phases.
- CW/VT - composite wing and vertical tail - use of ASTRAL/COGS strength resize and optimization modules for improved control surface effectiveness.
- V-22 empennage - multiple frequency avoidance
  - use of ASTRAL/COGS - frequency avoidance optimization.

APPLICATIONS OF  
STAND-ALONE DETAIL ANALYSIS  
PROCEDURES TO ACTUAL DESIGN AT GRUMMAN

We have been discussing finite-element analysis and optimization on what we might call the "vehicle system level," where the structure is sized to meet overall design objectives. Automated sizing is also performed on a more detailed component level, in which internal loads are extracted from the analysis and used as input to stand-alone design programs. One might be tempted to call the resizing performed by these programs: "component optimization." We simply refer to the procedures as "component sizing," since we usually have enough manufacturing side constraints that we simply resize by shaving or adding to the basic skin gage. We have used programs that perform this type of resizing on the F-14 wing outer panel, the shuttle wing (which utilized a special hat section), the integrally stiffened construction on the Gulfstream-II wing, and on the CW/VT graphite-epoxy wing to perform local panel-buckling analysis and smoothing of the ply layouts.

- F-14 wing outer panel
  - Y stiffener -- upper cover
  - Z stiffener -- lower cover
- Space Shuttle wing
  - special hat section
- Gulfstream-II and III wings
  - integrally stiffened construction
- CW/VT - composite wing and vertical tail
  - graphite/epoxy wing cover -- buckling/smoothing

## GRUMMAN OPTIMIZATION PROCEDURES

Grumman uses optimality criteria in structural resizing procedures that involve control effectiveness, divergence avoidance, deflection constraints, frequency constraints, flutter constraints and multiple constraints. The optimality criterion for a single design constraint may be stated simply as

At minimum weight, the change in the constraint parameter "F" per change in element weight is the same for all elements.

This criterion is the basis for the development of our resizing algorithms.

Grumman uses optimality criteria for overall sizing procedures that involve:

- control effectiveness
- divergence avoidance
- deflection constraints
- frequency constraints
- flutter constraints
- multiple constraints

### Optimality Criterion:

$\partial F / \partial w_i = \text{constant}$  -- at minimum weight the change in the constraint "F" per change in element weight is the same for all elements.

## GRUMMAN OPTIMIZATION PROCEDURES

In sizing for strength, we use resizing procedures that recognize detail design parameters pertinent to the type of construction employed. The appropriate procedure is tied to the "construction code" that is assigned to the element in the member data file. For example:

Construction Code A1 = Metallic - Isotropic construction  
The failure criteria give consideration to:

- Principal stress
- Modified effective stress ratio
- Minimum and maximum gages

We use structural sizing procedures that recognize detail design parameters where the structure is sized for strength:

- Metallic -- Isotropic
  - principal stress
  - modified effective stress ratio
  - minimum and maximum gages

## GRUMMAN OPTIMIZATION PROCEDURES (CONCLUDED)

Construction Code A3 = Metallic stiffened sheet

The failure criteria give consideration to:

- Stringer compression
- Stringer rigidity ( $EI/bd$ )
- Biaxial loading - sheet compression and shear
- Minimum and maximum parameter specification
- Stiffener gage is slaved to skin thickness

Construction Code C1 = Composite construction

The failure criteria give consideration to:

- Multi-ply orientation
- Fiber allowable stresses
- Balanced layer requirements
- Minimum and maximum number of plies in a given layer direction

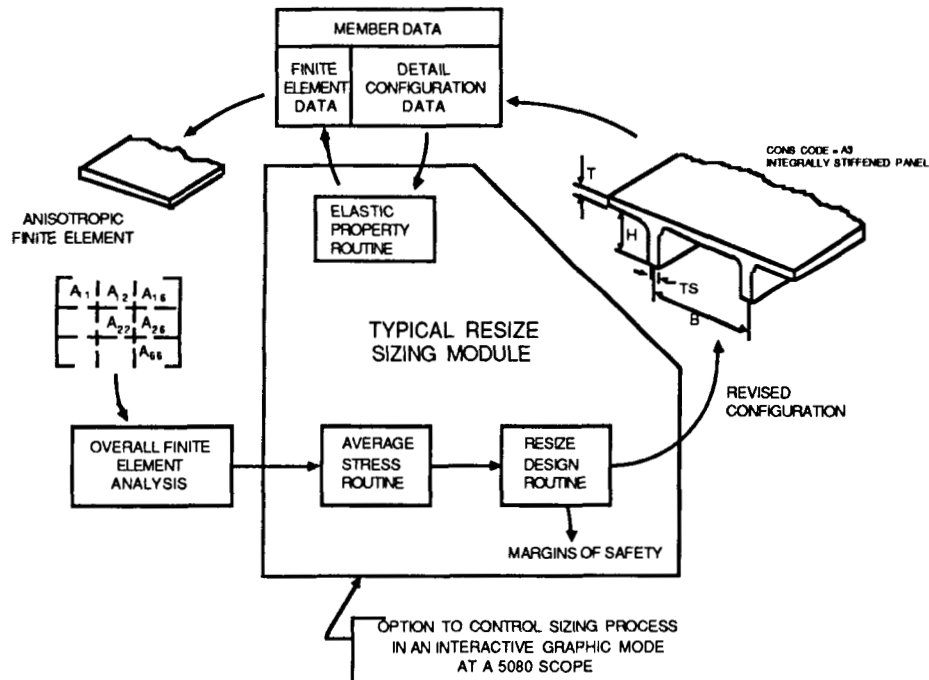
- Metallic Stiffened Sheet
  - stringer compression
  - stringer rigidity ( $EI/bd$ )
  - biaxial loading -- sheet compression and shear
  - minimum and maximum parameter specification
  - stiffener gage is slaved to skin thickness
- Composite Construction
  - multi-ply orientation
  - fiber allowable stresses
  - balanced layer constraints



## STRENGTH SIZING SCHEME

The following figure illustrates how our strength resizing scheme works. The illustration pertains to the Gulfstream III wing. The ASTRAL-COMAP member data contain regions that store detailed properties for a given construction as well as the usual finite-element type of data. The detailed construction properties are converted to anisotropic elastic constants and stored in the finite-element regions by appropriate subroutines. The structure is analyzed using standard finite-element techniques, then resized by use of the RESIZE module. This module uses the internal loads and a resizing scheme that utilizes the detail properties stored in the member data to perform rather sophisticated component sizing. The revised properties are output in a new set of member data. Multiple use of the analysis and resizing procedures leads to a fully stressed design that we have found to give realistic results.

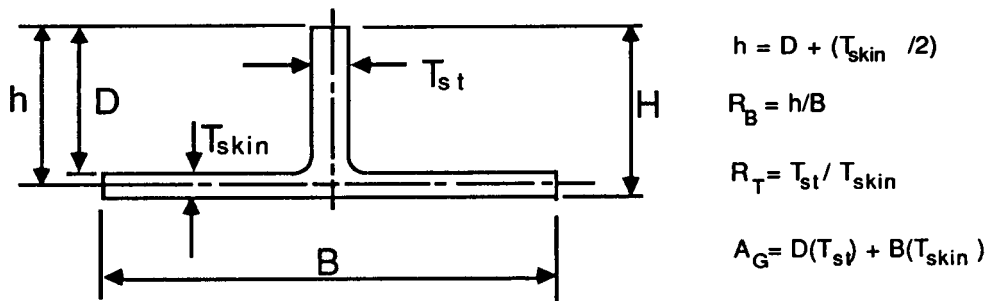
We might call this approach "component sizing" within an overall fully stressed design. We use the concept of a "construction code" to imply specified failure criteria for a given type of construction; hence, the finite-element model is merely the device for calculating internal loads. The actual finite-element model sizing is performed using realistic structural quantities that are tracked as attributes of the finite-element data.



INTEGRALLY STIFFENED PANEL  
CONSTRUCTION CODE A3

Design parameters that are stored for the integral stiffener are shown. This type of construction is used on the Gulfstream III wing, the A-6E inboard wing and the EA-6B inboard wing.

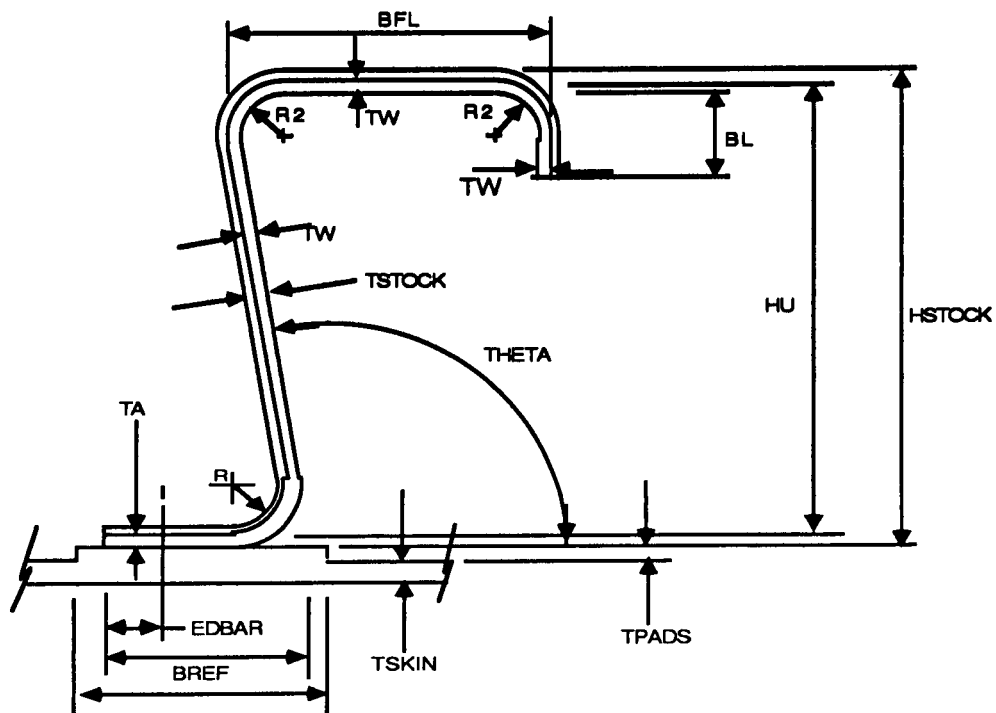
(Gulfstream-III wing, A-6E inboard wing, EA-6B inboard wing)



Z-STIFFENED SHEET  
CONSTRUCTION CODE A4

Detail parameters that are stored for the Z-stiffened sheet are shown. This type of construction is used on the E-2C and C-2A wings.

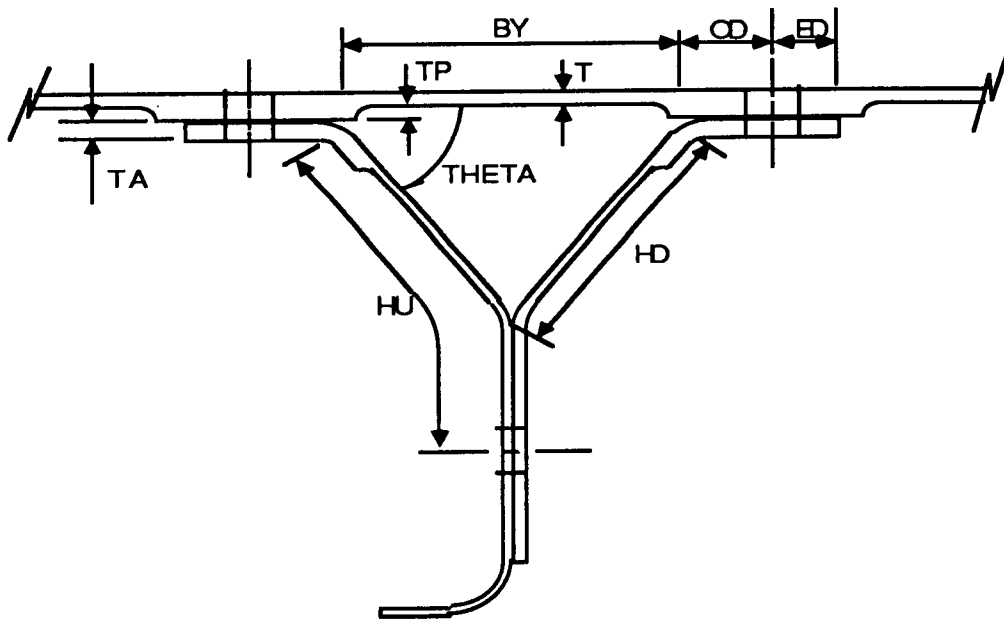
(E-2C and C-2A wing)



## Y-STIFFENED PANEL

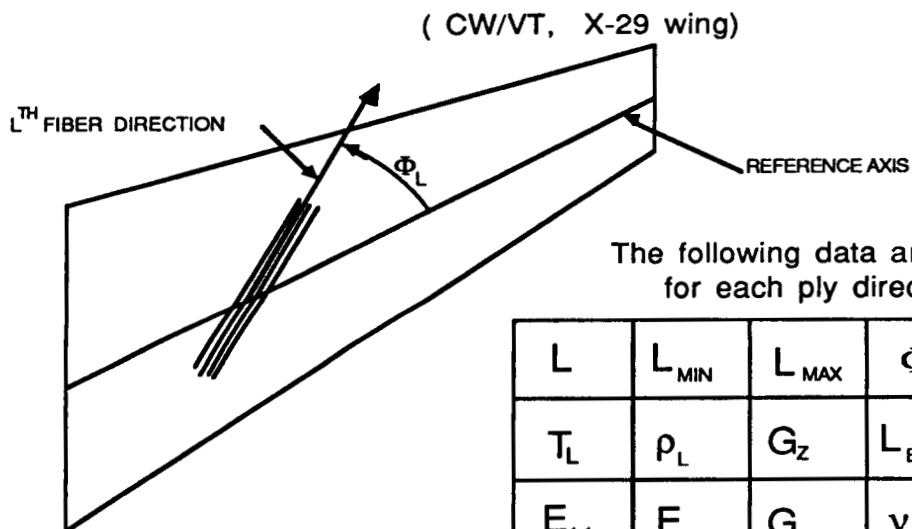
Detail parameters that are stored for the Y-stiffened panel are shown. This type of construction is used on upper cover of the F-14 wing outer panel.

(F-14 wing outer panel - upper cover)



# COMPOSITE CONSTRUCTION - CONSTRUCTION CODE C1

Detail parameters that are stored for composite construction are shown. This type of construction was used on the CW/VT wing and vertical tail and the X-29 wing. The code permits up to 6 different ply directions. To indicate what some of the parameters are, in a given direction,  $L$  is the number of plies,  $L_{MIN}$  and  $L_{MAX}$  are minimum and maximum allowed numbers of plies, respectively,  $L_{BAL}$  is a balanced layer clue (slaving, e.g., the number of layers in the +45 direction to the number in the -45 direction),  $L_{EVEN}$  makes provision to force the number of layers to be even in number, if desired for laminate symmetry.

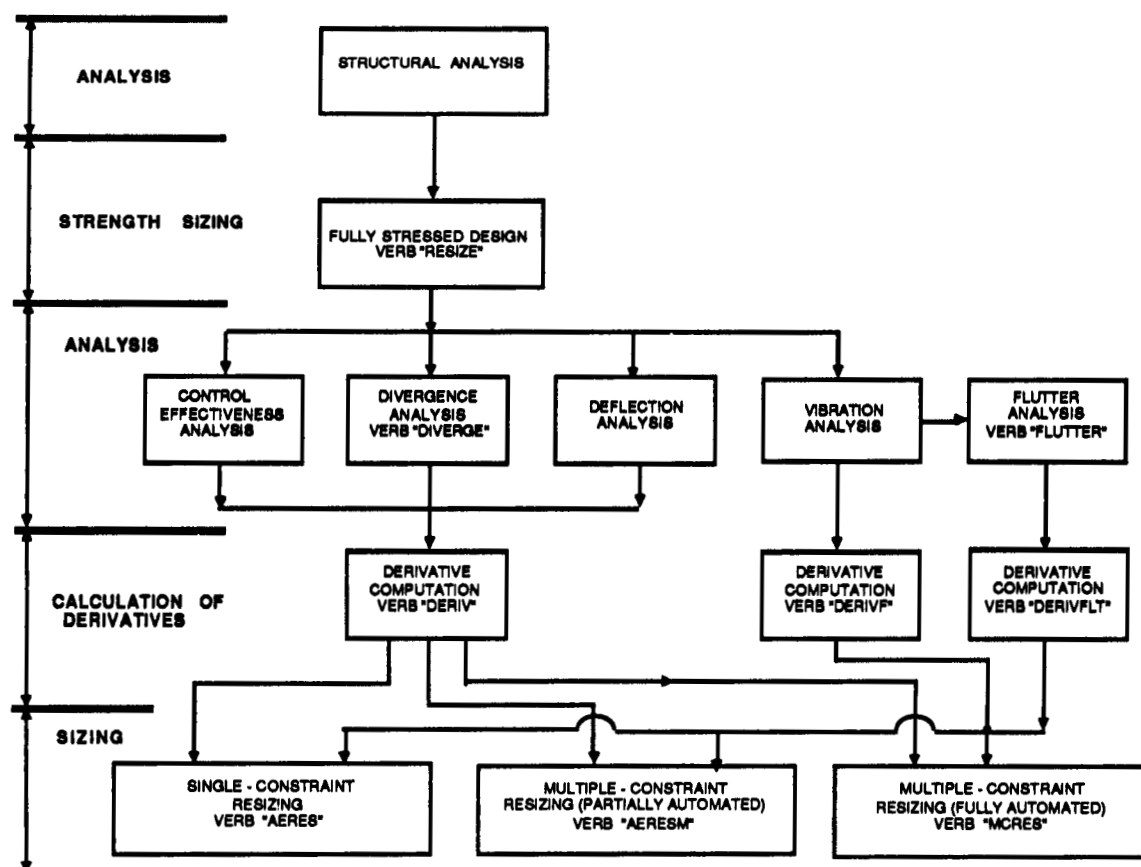


The following data are stored  
for each ply direction

$L$	$L_{MIN}$	$L_{MAX}$	$\Phi_L$	$L_{BAL}$
$T_L$	$\rho_L$	$G_z$	$L_{EVEN}$	$L_{ROC}$
$E_{11}$	$E_{22}$	$G_{12}$	$\nu_{12}$	
$F_{1T}$	$F_{1C}$	$F_{2T}$	$F_{2C}$	$F_s$

## STRUCTURAL OPTIMIZATION PROCEDURES

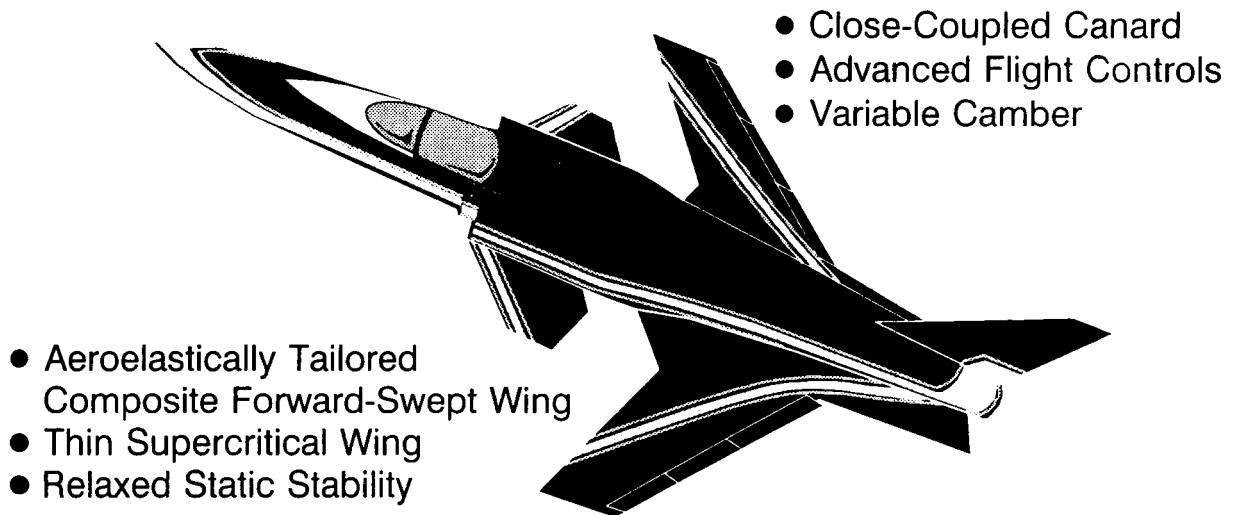
Application of the structural optimization procedures usually begins by performing a structural analysis to obtain displacements and internal loads. This is followed by a strength sizing using the RESIZE module. The analysis and resizing cycle is normally repeated three or four times (our experience indicates that for realistic structures, convergence usually occurs within three to five cycles). We next perform any number of analyses to calculate the specific quantities of interest such as control effectiveness, divergence speed, a specific deflection, modes of vibration, or flutter speeds. This is followed by the calculation of derivatives of these quantities with respect to element weight using modules such as DERIV, DERIV or DERIVFLT. The derivatives are then used in the resizing modules: AERES which performs resizing for a single constraint, AERESM which is a partially automated procedure for performing resizing when there are multiple constraints or MCRES, which is a fully automated procedure for performing resizing for multiple constraints. The calculation of derivatives and subsequent resizing is cycled until the desired result is obtained.



## THE X-29 FORWARD-SWEPT-WING DEMONSTRATOR AIRCRAFT

Automated design and analysis procedures played a major role in the development of the X-29 demonstrator aircraft. The design of this vehicle incorporates several advanced technology features as shown here. Particularly pertinent to our discussion is the work that was done to incorporate aeroelastic tailoring in the design of the wing covers, with the goal of minimizing the weight increment needed to avoid static divergence. A detailed discussion of the preliminary design work leading to the X-29 is given in Ref. 23.

# Grumman/DARPA X-29A Advanced Technology Demonstrator Technology Features

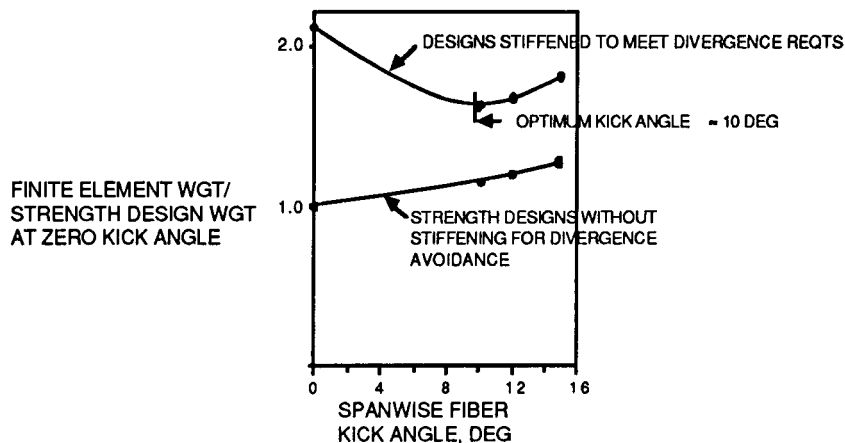


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## FORWARD-SWEPT WING FEASIBILITY STUDY

Our initial efforts in the design of a forward-swept wing were in a feasibility study we performed for DARPA in 1977. The study examined a relatively high-aspect-ratio wing having variable sweep. A goal was to investigate various configurations of composite cover skins with the objective of minimizing the weight increment required to avoid static divergence. Both beam and coarse-grid, finite-element models were employed to study various materials and laminate configurations with regard to their effect on divergence and flutter characteristics and to identify the weight increments required to avoid divergence. As an example of one part of the study, it was desired to evaluate the benefits of induced bend/twist coupling caused by kicking the spanwise fiber direction forward of the nominal structural axis. Four kick angles were examined with the use of our optimization procedures. Some results are shown in the sketch shown here. We see normalized weight variations for the wing model as obtained for strength-based designs, via fully stressed design, in the lower curve. The upper curve shows the effect on weight when each of the strength designs is stiffened to meet a critical divergence-speed requirement. It may be noted that the optimum kick angle is about 10 degrees.

- Examined feasibility of a variable sweep wing that used advanced composites to minimize weight increment to avoid static divergence
- Used beam and finite-element models and optimization methods to:
  - Assess behavior of various materials & ply configurations for covers
  - Provide estimates of divergence & flutter behavior
  - Estimate weight increments for divergence prevention





## X-29 PRELIMINARY AND FINAL DESIGN

In a later "Forward Swept Wing Demonstrator Technology Integration and Evaluation Study," conducted by Grumman for DARPA and the U.S. Air Force, we transitioned our design concepts to a fixed-wing configuration and utilized structural optimization technology in what was to become a preliminary design effort for the X-29. We adopted a wing cover arrangement that uses 0/90/±45 degree graphite-epoxy laminates which are rotated about 9 degrees forward of the nominal structural axis. This material arrangement offers favorable bend/twist coupling while maintaining high bending stiffness and linear stress/strain behavior. The 9-degree rotation angle comes about from our findings in the feasibility study and the added benefit that fiber continuity is preserved across the airplane centerline. We again used our fully stressed design and divergence optimization tools to size the wing covers and substructure. Gages that were identified as being governed by divergence requirements were maintained as minimums in the subsequent final design effort.

### **Preliminary Design**

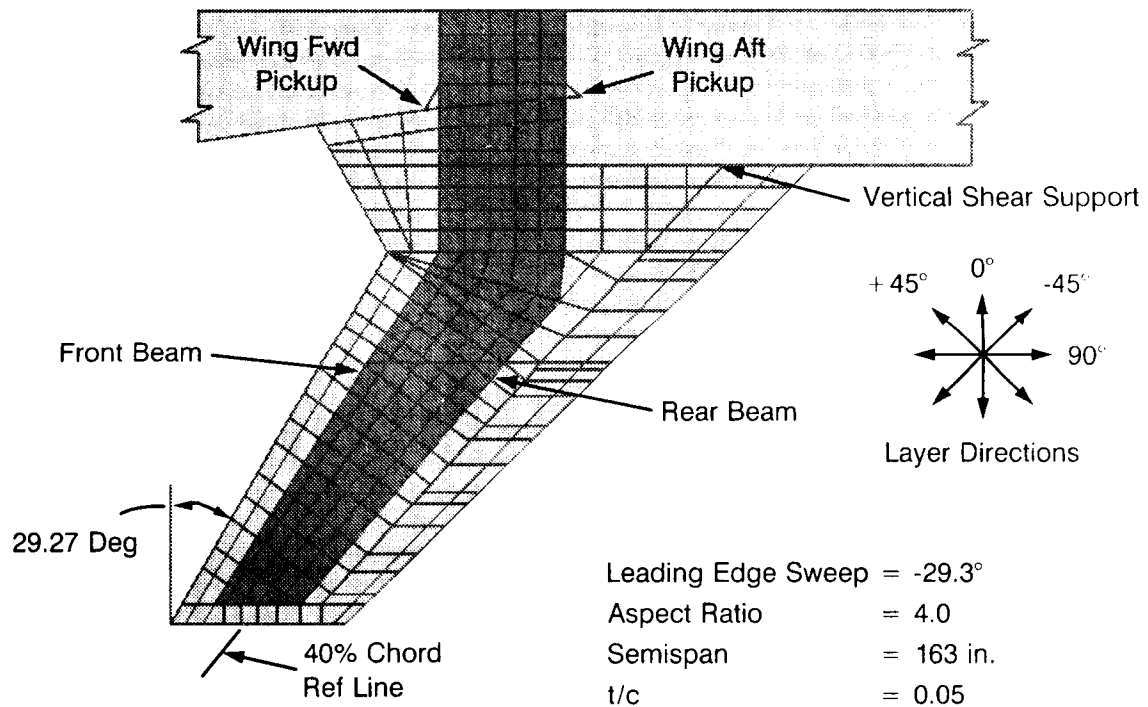
- Transitioned to fixed wing configuration utilizing graphite/epoxy cover skins of 0/90/± 45 deg plies. Laminates were balanced in ± 45 deg directions and were rotated approximately 9 deg forward to
  - produce favorable bend/twist coupling
  - maintain high bending stiffness
  - provide linear stress/strain behavior to limit load
  - preserve fiber continuity accross airplane centerline
- Employed fully stressed design and automated optimization to size wing for divergence speed requirements

### **Final Design**

- Increased model complexity and expanded number and type of design loading conditions. Used fully stressed design while maintaining as minimums the numbers of plies identified in the preliminary design as required for divergence avoidance

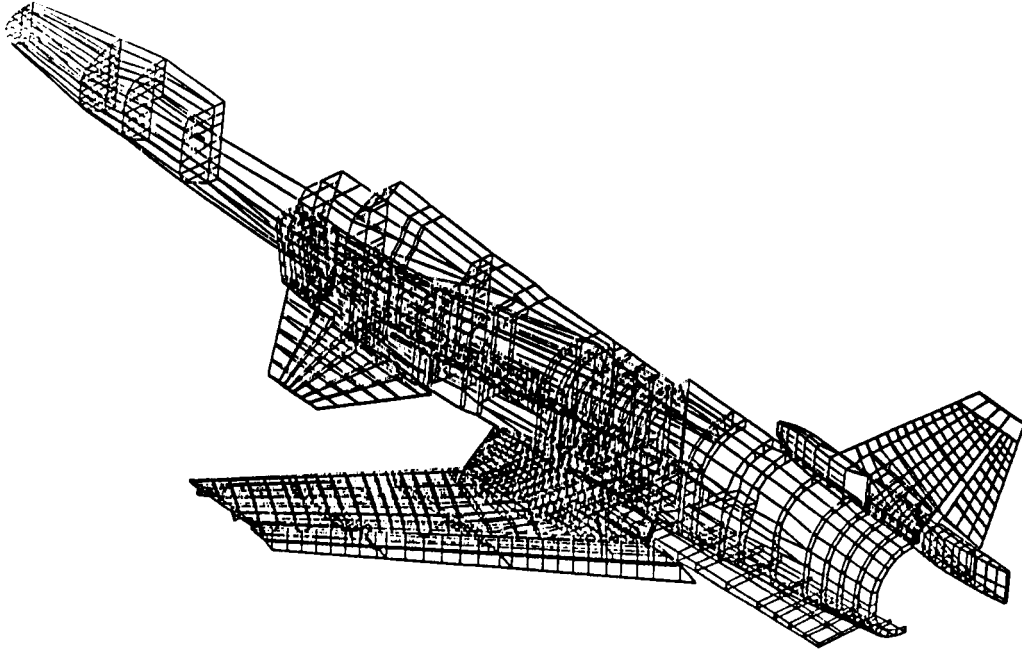
# PRELIMINARY DESIGN DEMONSTRATOR WING AND FINAL X-29 FINITE-ELEMENT MODEL

Here we have a planform of the wing model used in the technology evaluation and preliminary design work. This is followed by an isometric view of the final half-aircraft, finite-element model of the X-29.



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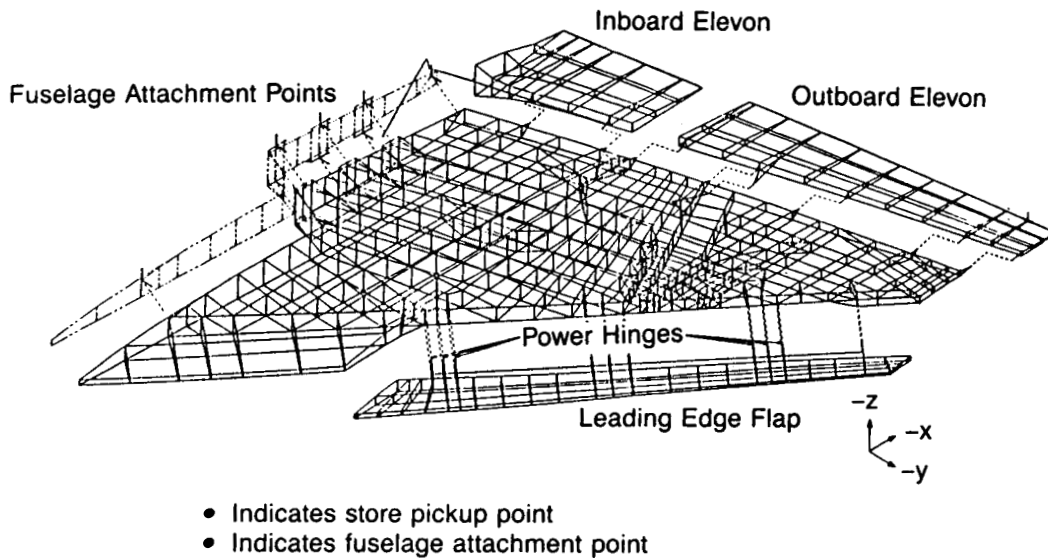
# **X-29 Forward Swept Wing Demonstrator Aircraft**



## FINITE-ELEMENT MODEL OF CW/VT WING

The CW/VT wing is a multispar configuration having graphite-epoxy covers and metallic substructure. It is attached to the fuselage at 8 points. Movable surfaces consist of a leading-edge flap and inboard and outboard elevons. The covers are modeled as anisotropic membrane panels; ribs and spars are represented by bars and shear panels. The total model contains about 3100 members, 3400 degrees of freedom and approximately 6000 design variables (which account for the individual ply directions in the covers).

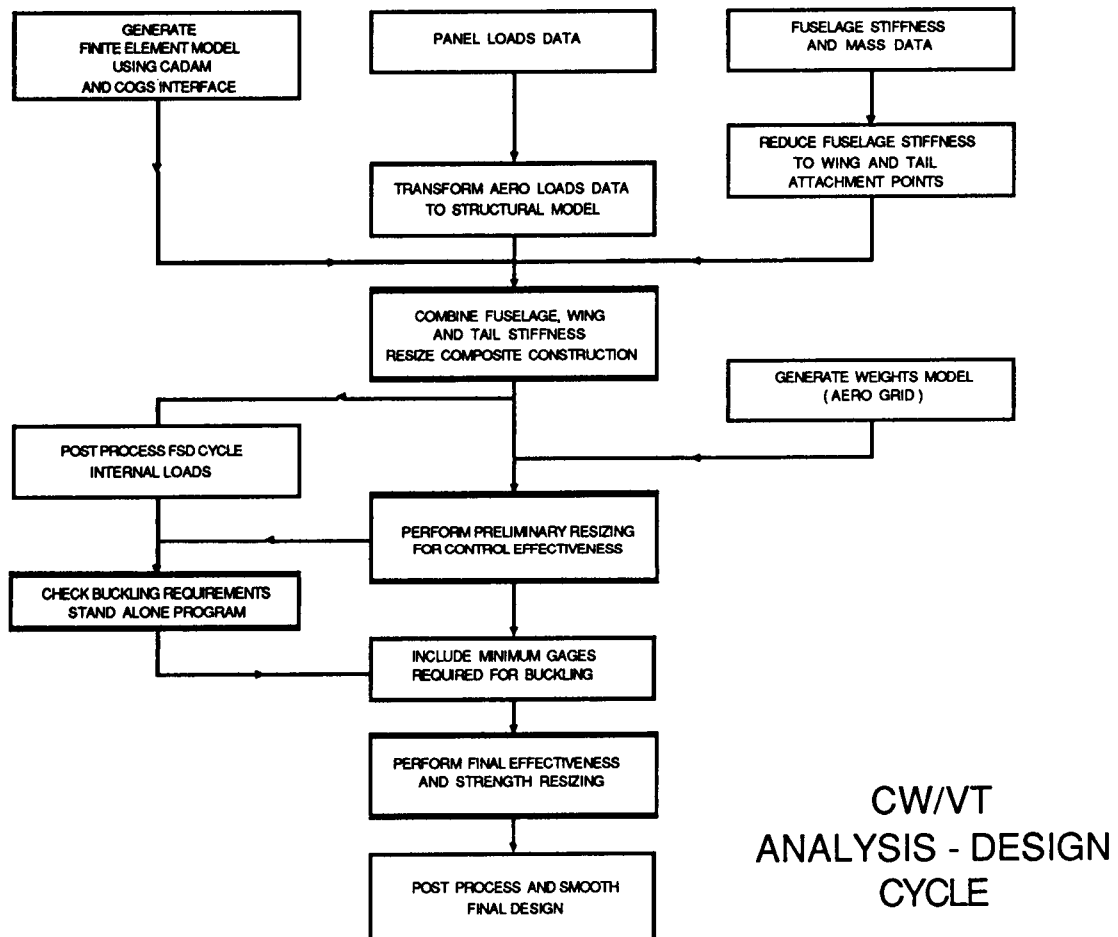
The structure was analyzed and sized to meet strength requirements for 102 flight design conditions. For the covers, strength requirements were based on maximum allowed fiber strains and panel buckling avoidance. Control-surface effectiveness requirements also played a major role in the design of this relatively thin wing. These requirements involved both pitch and roll, as well as ratios of pitch moment to hinge moment and roll moment to hinge moment, at Mach 0.9 and 1.2. The design was checked for flutter and leading-edge flap divergence, neither of which had any significant impact on the final design.



## CW/VT DESIGN/ANALYSIS CYCLE

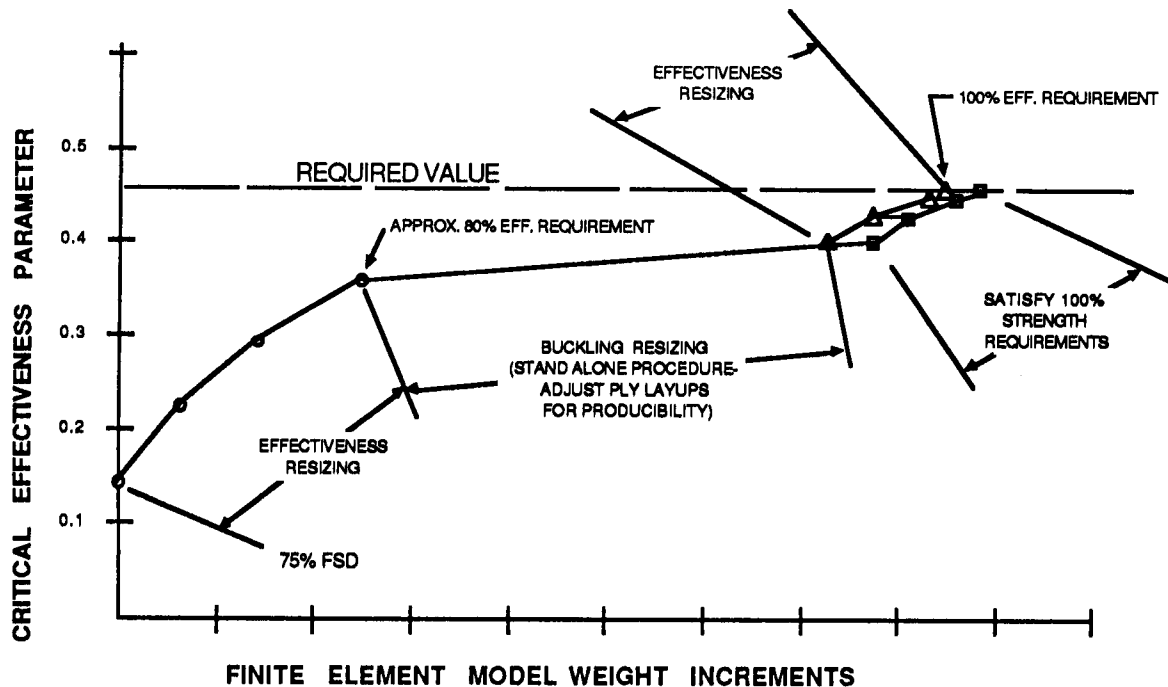
The design/analysis cycle is shown below. Initial tasks consisted of generating the finite element model using CADAM and our COGS interface. The prime contractor supplied panel-point loads that were transformed to the structural model. They also provided stiffness and mass data for the fuselage. The fuselage stiffness matrix was reduced to the wing and tail attachment points and coupled with the wing and vertical tail stiffness matrices.

Several design/analysis cycles were performed by Grumman for the wing and vertical tail. Based upon experience gained in the early cycles, we established a rather pragmatic approach to obtain a near-minimum-weight design in the final design cycle, in which requirements for strength, panel buckling avoidance and control-surface effectiveness were treated in a somewhat interactive way.



## CW/VT WING SIZING PROCEDURE

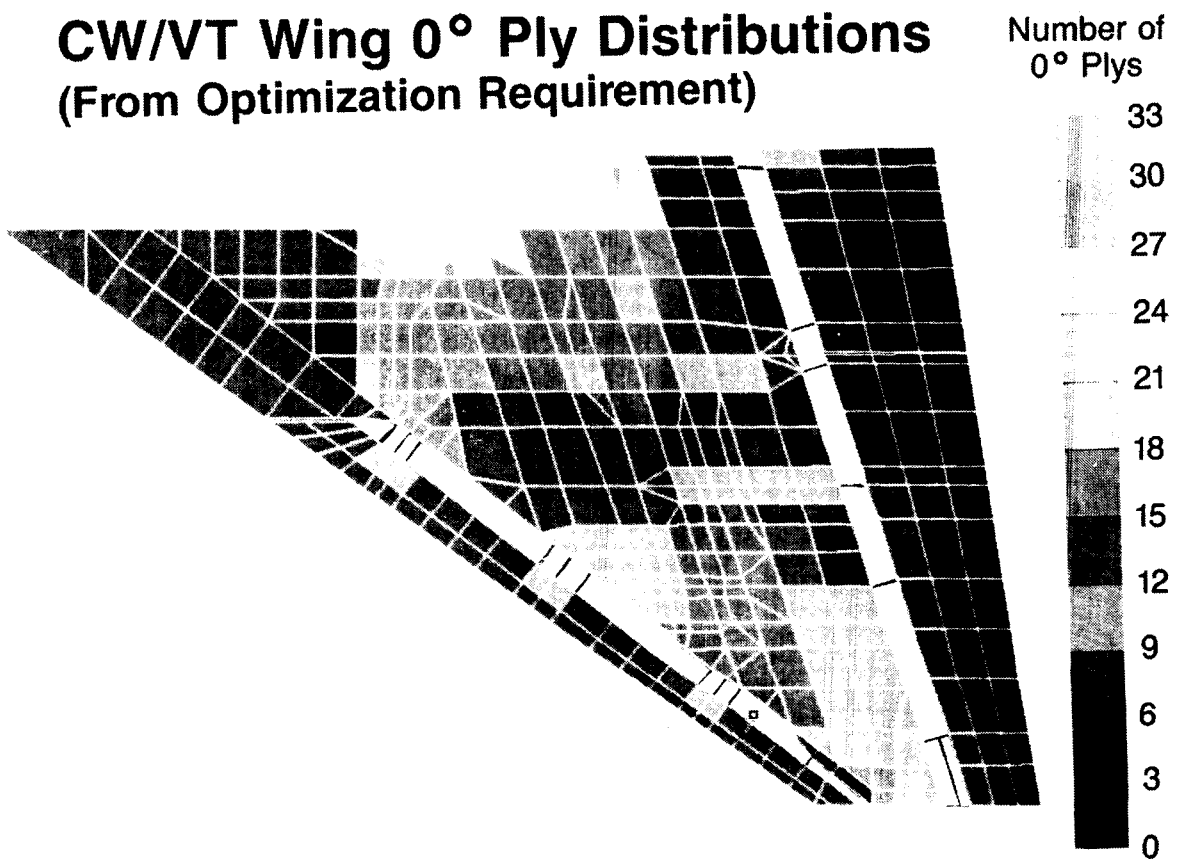
The final sizing procedure and results are summarized in the figure below. We have plotted wing finite-element model weight increments along the horizontal axis and the governing control-surface effectiveness parameter along the vertical axis. The required value of the parameter is shown as the horizontal line. Initially, we generated an FSD design for 75% of applied ultimate load. We then performed effectiveness resizing and brought the design to a point where the effectiveness parameter was approximately 80% of its required value. The buckling resizing and adjustments of the ply layups for producibility added additional weight increments and brought the effectiveness parameter to about 85% of the required value. Additional resizing to increase control effectiveness proceeded along the points marked by triangles in the upper portion of the curve. Along with each of these points are side-step increments required to satisfy 100% of ultimate load. All but the last of these latter points (marked by squares) represent designs which satisfy full strength and buckling-avoidance requirements but which compromise the full effectiveness requirement, should such a compromise be desired in the face of the identified weight increments.



## CW/VT WING 0° PLY DISTRIBUTION

Here we see the 0°-ply distribution for the lower cover of the CW/VT wing. The number of plies are color coded. The COGS system allows us to display a wide variety of information in an interactive graphics environment. For example, since we store various derivatives within regions of the member data, we can display them as well. We have found displays of this type of information to be particularly useful, not only in giving us important information about the design, but also as an aid in checking the realism of the model.

### CW/VT Wing 0° Ply Distributions (From Optimization Requirement)



ORIGINAL PAGE  
BLACK AND WHITE PHOTOGRAPH

## CONCLUSIONS

Integrated structural analysis and design systems and structural optimization procedures are being used in a production environment. Successful use of these systems requires experienced personnel. Interactive computer graphics can and will play a significant role in the analysis/optimization/design/manufacturing area. Today, we talk about collocating a team of people that include analysts, designers and manufacturing engineers on a given project so that they can interact via a common system. Practical structural optimization procedures are tools that must be made available to the team.

Much work still needs to be done to tie finite-element modeling to actual design details which are being tracked on systems such as CADAM or CATIA.

More work needs to be done to automate the detailed design and analysis process -- more emphasis should be placed on the real design problems.

## CONCLUSIONS

Integrated structural design and analysis systems, and structural optimization procedures are being used in the production environment.

- Successful use of these systems requires experienced personnel.
- More work needs to be done in developing data base systems that will track structural detail and permit better means for controlling the finite-element model idealization.  
(Example: Tie CADAM -- structural modeler -- analysis -- structural design)
- More work needs to be done to automate the detailed design and analysis process. (Example: Incorporate panel buckling and internal load redistribution due to post buckling)



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